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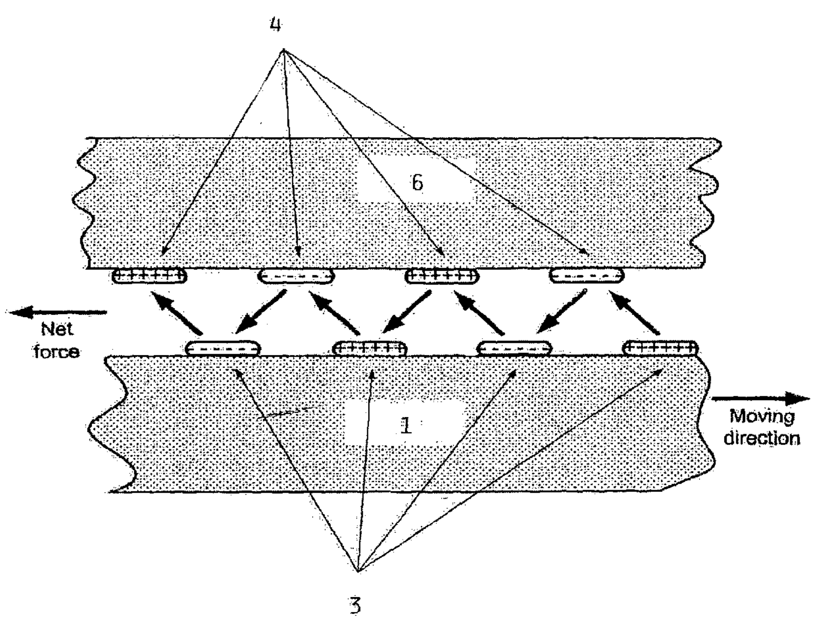
[Continued on next page]

(54) Title: MINI-KRAFTFORMER



(57) **Abstract:** A micro-electromechanical energy transformer comprising a stationary element (6) with a planar surface and a movable element (1) with a planar surface (1) arranged in such a manner that an air gap arises between the two plane surfaces (1). A first electrode system (4) belonging to the stationary element (1) and co-operating means (3) belonging to the movable element (1) create an electrical field in the air gap. The movable element (1) is integrated in an elastic mechanical element (1,2) such that the movement takes place through bending, for instance oscillation, of the elastic mechanical element (1,2).

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Technical Area

The invention concerns a micro-electromechanical system (MEMS) for mechanical actuation and transformation of pneumatic/hydraulic, mechanical and electrical energy.

State of the art.

Micro-electromechanical units/systems (MEMS) are different from other traditional electromechanical systems among others in their method of production and the materials used. These units are produced mainly by processes for production of semiconductor circuits/chips. Typically, the units are produced of silicon or glass. Typical processes applied are photo lithography, etching (for example DRIE – Deep Reactive Ion etching), doping, epitaxial growth and deposition of (metallic) materials (sputtering).

These processes make possible the production of small units with very small geometrical details (< 1 μm). The production methods are especially suitable for high volume production; the costs related to design and production of mesh are relatively high. For a high volume the component price can become very low, just as for integrated circuits.

A common problem for micro-electromechanical units is tribology, i.e. frictional forces and wear between two gliding surfaces. The coefficient of friction can be very high (approximately 1000 times higher than for steel) such that the direct contact between movable elements becomes very unfavourable when the relative speed is high. This results in major limitations for the functionality of the units and the problem is given much consideration in the research community.

The publication "An electrostatic induction micromotor supported on gas-lubricated bearings" by L.G.Frechette et al, pp 290-293, Proc. MEMS 2001. 14th IEEE International Conference of Micro Electro Mechanical Systems, New York, USA, 2001, describes a rotating electrical machine with a pneumatic bearing. The rotating element (a disk shaped rotor) is kept suspended from the stationary element by control of the pressure on both sides of the rotor plate. In this manner a direct contact between the two gliding surfaces is avoided. The problem with this design is that the unit requires a pneumatic control system in order to keep the rotating plate in the correct position, especially in cases where the unit vibrates.

The publication "Vibration-to-Electrical Energy Conversion" by S.Meininger et al, pp 48-53, Proc. of ISLPE99, San Diego , USA, 1999, describes a micro-electromechanical unit for conversion of mechanical energy to electrical energy that needs no bearing in the traditional sense of the word. The movable element is suspended between two beams that are stretched/bent with the movement of the swinging matter. The energy conversion takes place when using a variable capacitance in which the stationary and movable elements are designed as chambers that overlap (comb). The unit described in the publication has an effect of 8 μW. The effect is fundamentally restricted by two factors, the force between the stationary and movable elements and the frequency (speed) of the movable element(s). In this unit the force is restricted by a low capacitance due to a small area even though the comb has many teeth. MEMS units are typically planar structures and it is therefore desired that the force should act in an air gap that is parallel to the substrate. This is not the case in the present unit.

In US patent no. 4,943,750 "Electrostatic micromotor" by Howe et al a great selection of embodiments are shown where the energy interaction between the stationary unit and movable unit takes place in a air gap that is parallel to the substrate. Both rotational and translatory movement is described. The mounting of the movable unit can be pneumatic and/or electromagnetic (levitation). The patent describes several principles for conversion of mechanical and electrical effects. The methods can be divided into two main groups: Electrical and mechanical. In traditional electrical machines it is only the magnetic forces that are used. In the case of micro-machines transformation of effect based on electrical forces is sometimes preferred. Both electrical and magnetic induction is described in the patent. The output of the unit can be substantially enlarged since the area where the transformation of power takes place can be large. Further the number of revolutions of the rotating plate that comprises the rotor can be high. In "An electrostatic induction micromotor supported on gas-lubricated bearings" by L.G.Frechette et al, pp 290-293, Proc. MEMS 2001. referred to above a comparable structure is used in a unit with 900,000 rpm and a performance of 3W. There are not published any results that show that these units have a long longevity. It is presumed that this may be due to problems with the mounting.

US patent no. 5,043,043 "Method for fabricating side drive electrostatic micromotor" by Howe et al. describes another embodiment where the power interaction takes place in an air gap radially to the rotational axis of the rotor (as in the traditional electrical

machines). For this motor the area of power interaction will be smaller and dependent on the thickness of the rotating plate.

Micromachines can further be produced by taking advantage of piezoelectric effect to create ultrasonic waves. However can these only be used as motors and not as generators. The article "Smart motors in Germany" by W. Seeman , pp 472-483, Proceedings of SPIE, vol 3321, 1998 describes such a motor.

Purpose of the Invention

One purpose of the invention is describing a technical solution that solves several of the above described limitations to the present state of the art.

Another purpose of the invention is providing an arrangement for transforming the mechanical energy in a moving, elastic element to electrical energy, which further can be used to provide electrical energy to further electrical circuits.

It is also a purpose of the invention to provide an arrangement whereby an elastic mechanical element which can be set in motion is included in a generator that can produce electrical effect.

It is a further purpose of the invention to provide an arrangement in which an elastic mechanical element can be set in motion through the supply of electrical energy in order to produce a fluid stream.

It is still a further purpose of the invention to provide an arrangement wherein an elastic mechanical element can be set in motion or translocation through the supply of electrical energy in order to form an actuator arrangement.

More especially the invention is aimed at providing different embodiments for achieving the above mentioned purposes without applying mechanical elements that have immanent tribology problems.

The purpose of the invention is achieved according to the invention through a micro-electromechanical energy transformer that comprises a stationary element with a planar surface and a movable element with a planar surface that are arranged in such a manner that there is an air gap between the two planar surfaces and where a first system of electrodes belonging to the stationary element and co-operating means belonging to the movable element can form an electrical field in the said air gap. The energy transformer is characterised by the movable element being integrated in an elastic, mechanical element such that the movement takes place through bending, for instance oscillation, of the elastic, mechanical element.

In one embodiment the energy transformer is adapted for use as a generator wherein mechanical energy is converted to electrical energy in that it comprises an electrical circuit in conjunction with the first electrode system wherein electrical effect is generated in the form of induced electrical current through the movement of the movable element, for example resulting from an oscillating fluid stream, and wherein the electrical circuit transfers electrical energy to an electrical cargo.

In a further embodiment the energy transformer is adapted for use as a motor or actuator wherein electrical energy is converted to mechanical energy through the inclusion of an electrical driver circuit in conjunction with an electrical energy source in order to supply the first electrode system with electrical energy in the form of electrical current such that the resulting electrical forces between the stationary and the movable elements sets the movable element in motion.

Further advantageous embodiments of the invention will appear from the dependent claims and the description.

Below are described the embodiments of the invention through examples. The examples are illustrated through the following enclosed figures:

Fig. 1 depicts an example of a planar rotor plate at the end of an elastic mechanical element in the form of a bendable beam.

Fig. 2 depicts a cross section seen from the front and perpendicular to the direction of movement of a beam.

Fig. 3 shows a typical structure seen from the side in a cut through a swinging beam.

Fig. 4 shows the swinging beam in the energy transformer seen from above.

Fig. 5 depicts how electrostatic forces act between the rotor electrodes and the stator electrodes.

Fig. 6 shows a schematic view of an unfolded cross section of the surface of both stator and rotor (planar rotor plate) against the air gap where the electrodes are placed.

Fig. 7 depicts the rotor electrode system arranged on the upside of the swinging beam.

Fig. 8a shows a cross sectional view of the air gap with the electrode system of the stator and with a permanently polarised material (electret) in the rotor instead of an electrode system as on figure 7.

Fig. 8b shows a cross sectional view of the air gap with the electrode system of the stator and with a space charged material in the rotor instead of an electrode system as on figure 7.

Fig. 9 shows the electrical coupling when the unit is used an generator.

Fig. 10 shows a cross sectional view of the air gap with the electrode system of the stator and with conductive material on the rotor surface (induction machine).

Detailed description

In the following it is described firstly how the micro-electromechanical energy transformer is designed and how it can be used as an electrical generator. Figure 1 shows a preferred embodiment of a movable element (1) with a planar sheet executed as a planar rotor plate 1. The plate 1 is set in motion back and forth along a curve, typically approximately an arch of a circle, when the mechanical element 2 is bent. In figure 1 the elastic mechanical element 1,2 is in principle formed as a beam 2. The beam 2 is set in a swinging motion by an alternating pneumatic pressure on both sides of the beam, for instance through oscillations in a fluid stream directed against the longitudinal direction of beam 2. The beam 2 and the planar rotor plate are typically produced from a larger silicon chip. The beam 2 and the plate 1 have no contact with other elements, except for the beam being suspended from the silicon chip at one end 22 as shown on figure 1.

The beam can be mounted in such a manner that the movable end is turned against the flow direction of a fluid stream or it can be mounted such that the movable end is turned towards the flow direction. The structure of figure 1 can be implemented in MEMS technology (Micro-electromechanical system) among others.

On figure 2 it is shown how the movable element, the plate 2, has no contact with the stationary element, in this case the stator structure 4,6 or the underlying substrate 7. The electrodes 4 are placed on the backside of the stator plate 6 and on the topside of the rotor plate 1. The beam 1 is driven to the right on the figure by a higher pneumatic pressure P_1 in a first chamber 20 on the left hand side of the beam 2, than pressure P_2 in a second chamber 21 on the right hand side of the beam 2. The pneumatic energy, represented by air (gas) under pressure, is converted firstly to mechanical kinetic energy as the air (the gas) is setting the beam in motion. This kinetic energy can be converted to electrical energy by the means of electrodes 3,4 on the plate 1 and on the upper edge of the cavernous space, i.e. on the underside of an upper glass plate 6 that represents the stator 6 in the construction.

Figure 3 shows a cross sectional view through the MEMS structure in a preferred embodiment of the power transformer in the longitudinal direction of beam 2. Beam 2 is etched from a substrate 5 that is bound to an underlying substrate 7. The structure is closed.for example with a glass plate 6, whereon also the stator electrode system 4 is mounted. In this manner the movable element 1 becomes an integral element of the elastic, mechanical element 1,2.

Figure 4 illustrates how the beam 2 is attached at its one end and will bend as shown when the planar rotor 1 is moving along a curvature on the underside of a stator 4 that is designed as a circular sector. The beam 2 is as mentioned preferable produced by etching (DRIE) from a larger Si-disk. This achieves a very good mechanical strength for the attachment of beam 2 to the remainder of the silicon piece. The planar rotor plate 1 will move along a curvature, approximately a circular curvature when beam 2 is bending.

The stiffness of beam 2, its mass distribution as well as the power from the pneumatic system determines the swing frequency. As an approximation of the first order it may be presumed that the speed of the planar rotor plate will be sinus variable with time. The motion between the stationary and movable element takes place tangentially to the air gap. The longitude of the air gap does therefore not change as a function of the air gap, which is a common problem with traditional capacitance actuators.

The movable element is as mentioned mounted on a bendable beam. This assures that the movable element does not come into contact with the stationary elements. The beam therefore defines a specific motion area for the movable element. The stiffness of the beam can be adapted to the application.

As opposed to a traditional electrical machine the power between the stator 4 and rotor 1 is electrical power arising from electrical charge and not magnetic power having electrical current as its source. In order to achieve an energy transformation the electrical power must work against (generator) or with (motor) the rotor direction of movement. Figure 5 illustrates how this can be accomplished. The charge along the air gap to both stator and rotor is varied between a given positive and negative value in such a manner that the net charge in stator and rotor is zero. When the positions of the charges in stator and rotor are dislocated as shown on the figure, this results in a net axial power to the left on the figure.

The forces between the movable element and the stationary element are transmitted in an air gap parallel to the substrate whereby an active surface typically will be 1x1 mm. Specific power density is limited; this means that the area where the power

transmission takes place should be as large as possible. In a preferred embodiment electric power interaction is applied between movable and stationary element. If the power in tangential direction between stator 4 and planar rotor plate 1 is constant the turnover effect will also vary as a sinus function with time. The speed variation with time is not of any vital importance for the function of the unit as generator.

It is possible to produce a charge distribution that moves along the air gap by arranging an electrode pattern as shown on figure 6. The electrodes in stator 4 are grouped in three phases all of which are to connected to their own AC voltage source 8, while the corresponding electrode pair on rotor in this case is connected to DC voltage source 9. The voltage sources connected to the stator 8 are alternating voltage sources that have a displacement phase of 120 degrees. Thus the charge distribution will move along the air gap as a wave. The speed is determined by the frequency of the voltage and the distance between the electrodes. In US Patent no 4,943,750 "Electrostatic micromotor" by Howe et al. a more detailed description is given of how a moving electrostatic field may be arranged. In order for the power not to change its direction and not to have a too large variation it is necessary that the velocity of the rotor and the electrical field from stator are the same. This is equivalent with the working principle of a common magnetic synchronous machine

Figure 7 illustrates the direct voltage electrode pattern 3 on the rotor 1,2,3. A "synchronous machine" that is based on electrical forces can also be produced without an electrode pattern on the rotor as shown on figure 7. An electrical field distribution that is stationary can as an alternative be mounted by using electret in rotor or through doping of space charges in rotor as shown in figure 8. The electret is a material that has a permanent polarisation. This results also in a "synchronous generator". One advantage with this structure is that is no need for an electrode pattern on the oscillating beam as shown on figure 6 . A disadvantage with this solution is that it is vulnerable to pollution in the form of dust. The permanent charge of the rotor will attract dust. This also applies to the DC-excitated rotor on figure 6, but in this case the polarity of the rotor electrodes can be altered after a certain time. Any dust that has collected on the rotor electrodes will then be set free.

The shown beam design according to the invention gives an improvement of the prior art as it makes it possible to have an electrode system on the movable element, i.e. the rotor, without the need for gliding contacts ("combs"). The electrode pattern on the planar rotor plate can be contacted by means of the swinging beam. This is not possible in cases where there is a rotating plate needing gliding contacts ("combs").

When the unit operates as a generator it is normally not connected to any external voltage source as shown on figure 6. It is not necessary as only the rotor needs to be placed in a voltage field in order for the unit to work. One example is the embodiment shown on figure 9. The stator in this instance is connected to a rectifier that is further coupled to a cargo. The advantage with such a system is that the need for a control system is minimal. A passive rectifier can operate without control and regulation. In order for the system to start it is possible to use a capacitor that applies a voltage on the rotor. When the unit is running the necessary maintenance voltage for the rotor can be collected from the stator. This is analogous with a traditional synchronous machine with static magnetising supplied from the stator clamps.

In the following a description is given for how the unit works as motor/generator. The micro-electromechanical unit is a linear motor where the moving element ("rotor") is mounted on a bendable beam that defines its area of movement. Somewhat simplified it can be said that the unit is a linear motor/generator where the movable element is a plate with a power efficiency tangential to the surface of the plate. The plate is supported on a bendable beam which defines the area of movement for the plate. The unit is then supplied with electrical power from an external source and converts this power to mechanical movement. The stator circuit is supplied by an external voltage generator. It can control both the amplitude and the frequency of the applied voltage. When the rotor is designed with DC-excitated electrodes as on figure 6 or electret or with space charges as on figure 8 this is a "synchronous motor drive". This requires a position sensor due to the need for knowledge of the mechanical position of rotor in order to operate the voltage in stator. Thus it requires a larger control and regulation system. As one example piezoresistive elements can be integrated on the beam 2 or on the plate 1, for example parallel to the beam electrodes 13 shown on figure 7 . By measuring the electrical resistance in these piezoresistive elements using one of several well-known techniques in the art, the swing of beam 2 can be calculated in a calculator unit and further be used in the control and regulation system for operating the beam movement.

In a preferred embodiment the motor is executed as an electroquasistatic (EQS) motor, see figure 10. This is analogous to a magnetic induction motor. In a motor based on electrical induction the surface of the rotor is doped such that the translocation current and the conductive current are of the same order. This means that the permittivity ε, the conductivity g and the frequency ω must be adapted to each other. The momentum arises

when the induced charge on the rotor surface is relocated in its position compared to the charge distribution on stator as the rotor moves asynchronous with the electrical field applied on the stator electrodes. An example of such a motor with a rotating rotor is given in the publication "Electroquasistatic induction micromotors" by S.F.Bart and J.L.Lang, pp 7-12, IEEE Micro-electromechanical Systems, New York, USA, 1989. In this case it is not necessary to know the exact position of the rotor. Deviation in speed between the rotor and the voltage wave erected by stator will change the retardation and thus the properties of the unit. However is the requirement for accuracy and complexity reduced in the operation and control system when the unit is operated in a swinging modus as compared with an embodiment of a synchronous motor.

Typical applications for the invention are power generators where the beam is set in motion by a fluid or air current. The energy of the moving fluid is then converted to electrical energy. The converse transformation of energy is also possible, i.e. when the invention is used as a pump motor to set the fluid in streaming motion in a pipe or a channel. The invention may further be used as an actuator for instance for actuation of valves. The power and position of the moving element can be driven by the electrical drive circuit with great precision in all areas of movement. Thus this makes possible the use of the invention as actuator for dosimeters and micro-manipulators. An especially good control with the position is achievable when a position sensor is included in the arrangement.

Patent claims:

1. A micro-electromechanical energy transformer comprising a stationary element (6) with a planar surface and a movable element (1) with a planar surface arranged in such a manner that an air gap arises between the two plane surfaces (1), a first electrode system (4) belonging to the stationary element (1) and co-operating means (3) belonging to the movable element (1) in order to create an electrical field in the air gap, charcterized in that the movable element (1) is integrated in an elastic mechanical element (1,2) such that the movement takes place through bending, for instance oscillation, of the elastic mechanical element (1,2).

2. An energy transformer according to claim 1, wherein the first electrode system (4) is a multiphased alternating voltage system.

3. An energy transformer according to claim 1, wherein the electrical field erected from the stationary element (6) and the electrical system mounted on the movable element (1) are moving synchronously.

4. An energy transformer according to claim 1, wherein said co-operating means (3) at the movable element (1) comprises a second electrode system (3).

5. An energy transformer according to claim 4, wherein the second electrode system is a direct voltage system that erects an electric field in the air gap that is stationary compared to the movable element.

6. An energy transformer according to claim 1, wherein said co-operating means (3) at the movable element (1) comprises areas with space charge dopings (10).

7. An energy transformer according to claim 1, wherein said co-operating means (3) at the movable element (1) comprises an electret material (11).

8. An energy transformer according to claim 1, wherein said co-operating means (3) at the movable element (1) comprises a conductive or semi-conductive surface on the movable element (1).

9. An energy transformer according to claim 1, wherein the elastic mechanical element (1,2) is principally designed as a beam fastened at one end.

10. An energy transformer according to claim 1, wherein the movement between the two planar elements (1,6) are mainly transitory with an approximately constant size of the air gap between the two planar elements.

11. An energy transformer according to claim 1, wherein the movable element (1) is moving approximately along a curve.

12. An energy transformer according to claim 4, wherein it comprises electrodes arranged along the bendable beam at least to its fastened end.

13. An energy transformer according to claim 1-7 and 9-12 adapted for use as a generator where mechanic energy is converted to electrical energy, further comprising an electrical circuit (14) attached to the first electrode system (4) where electrical energy is generated in the form of induced electrical current by movement of the movable element (1), for example caused by an oscillating fluid stream, and where the electrical circuit (14) transfers electrical energy to the electrical cargo (16).

14. An energy transformer according to any claim 1-12 adapted for use as a motor or as actuator wherein electrical energy is converted to mechanic energy, further comprising an electrical drive circuit (15) attached to an electrical energy source in order to deliver electrical energy to the first electrode system (4) as electrical current such that the resulting electric forces between the stationary element (6) and the movable element (1) sets the movable element (1) in motion.

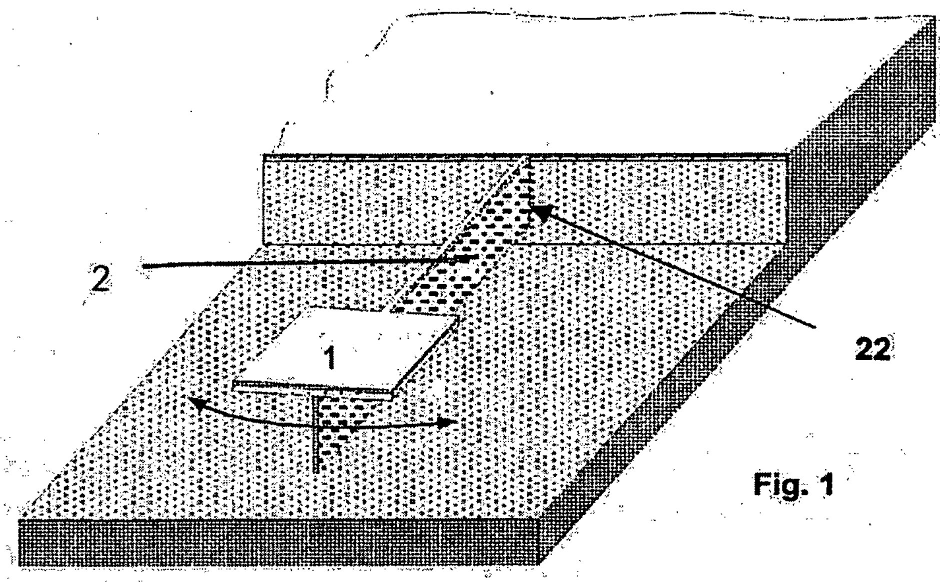

Fig. 1

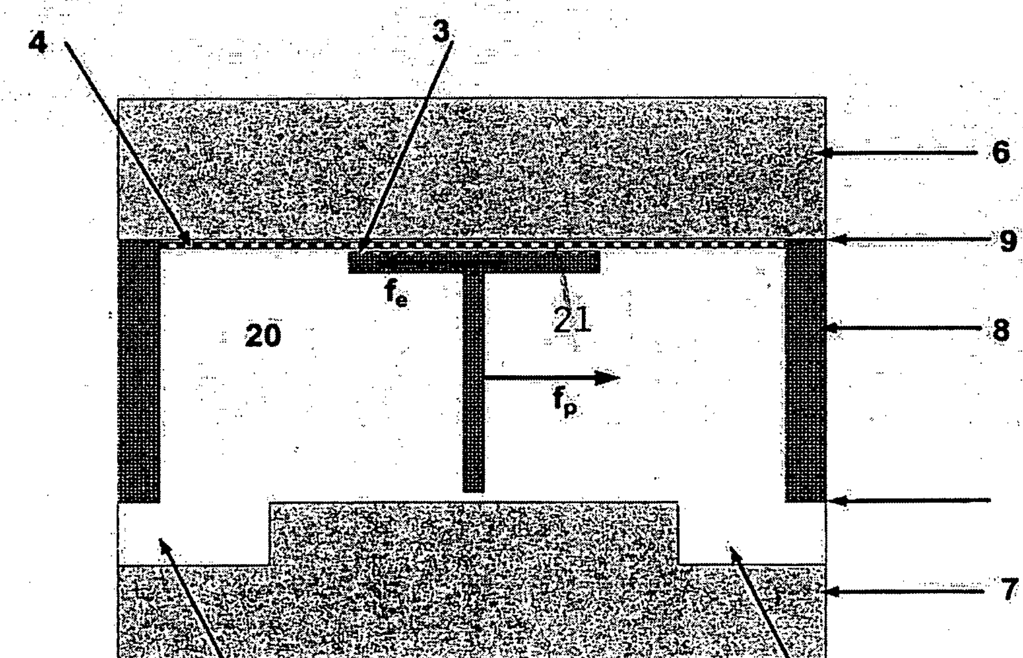

Fig. 2

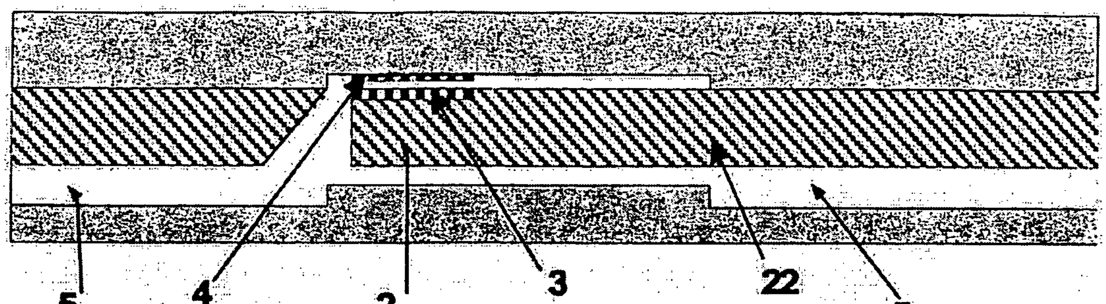

Fig. 3

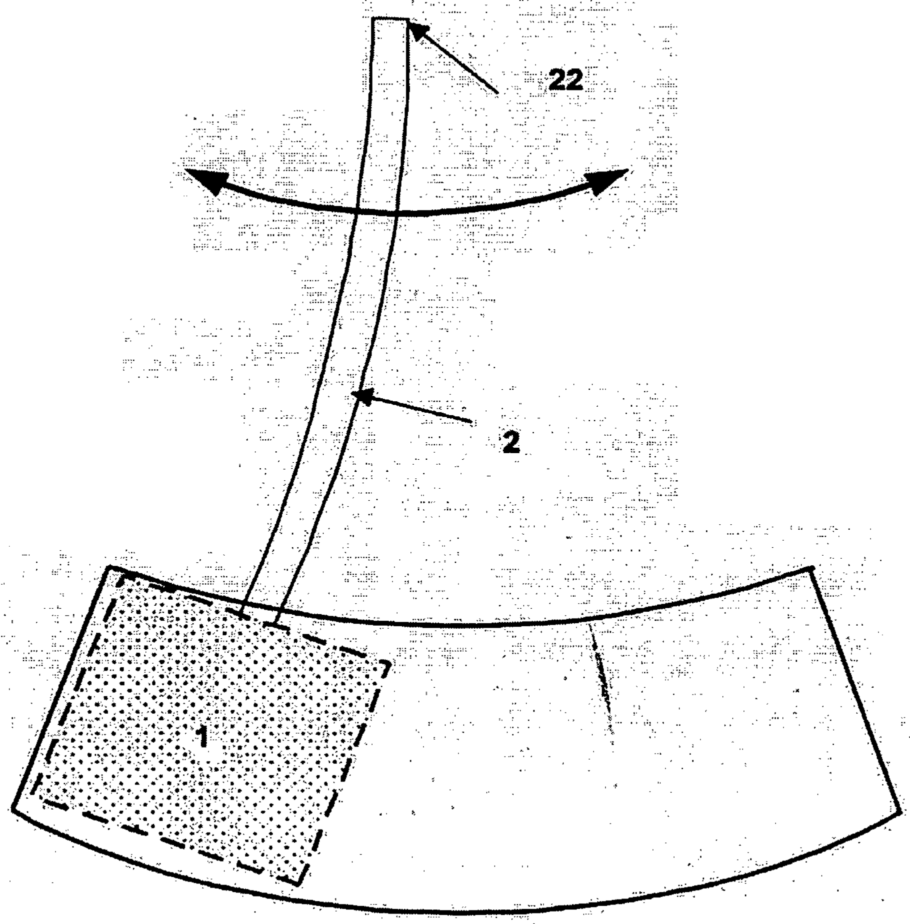

Fig. 4

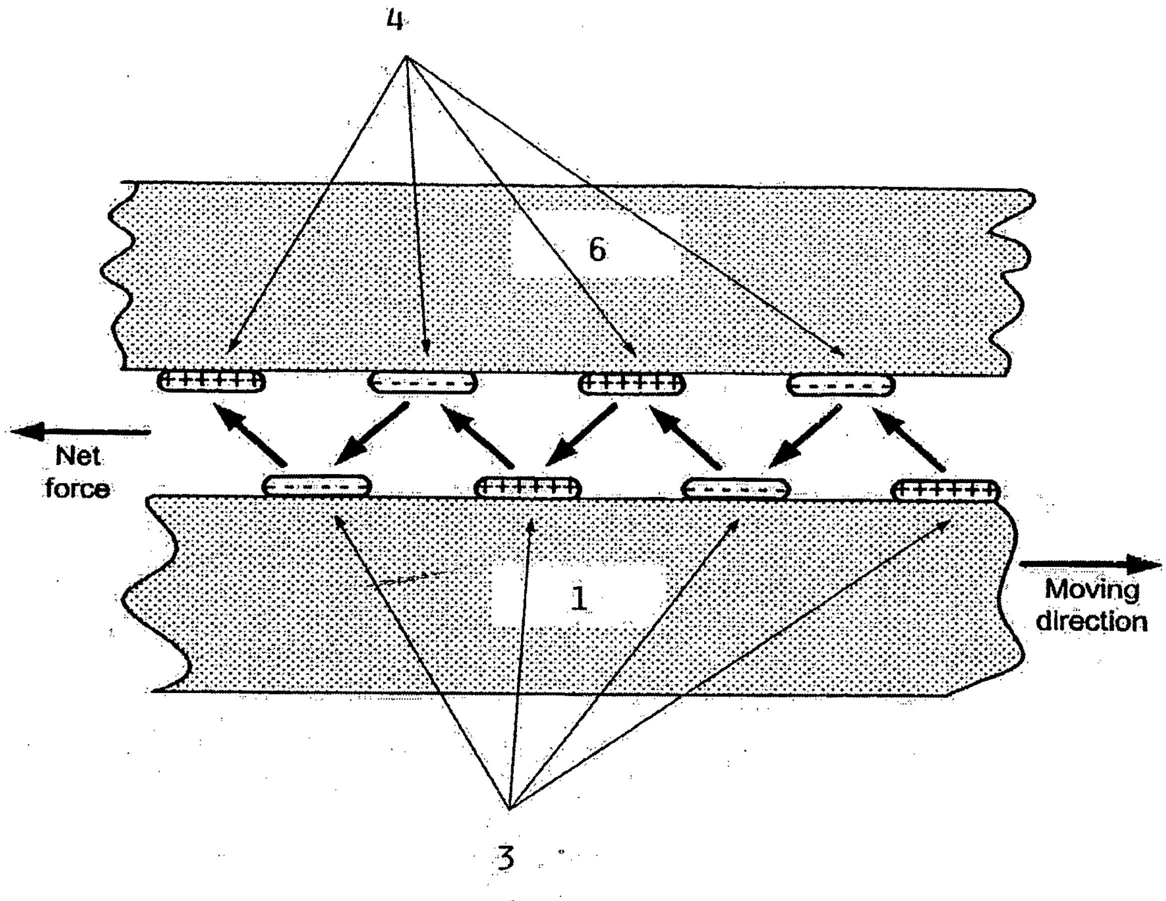

Fig. 5

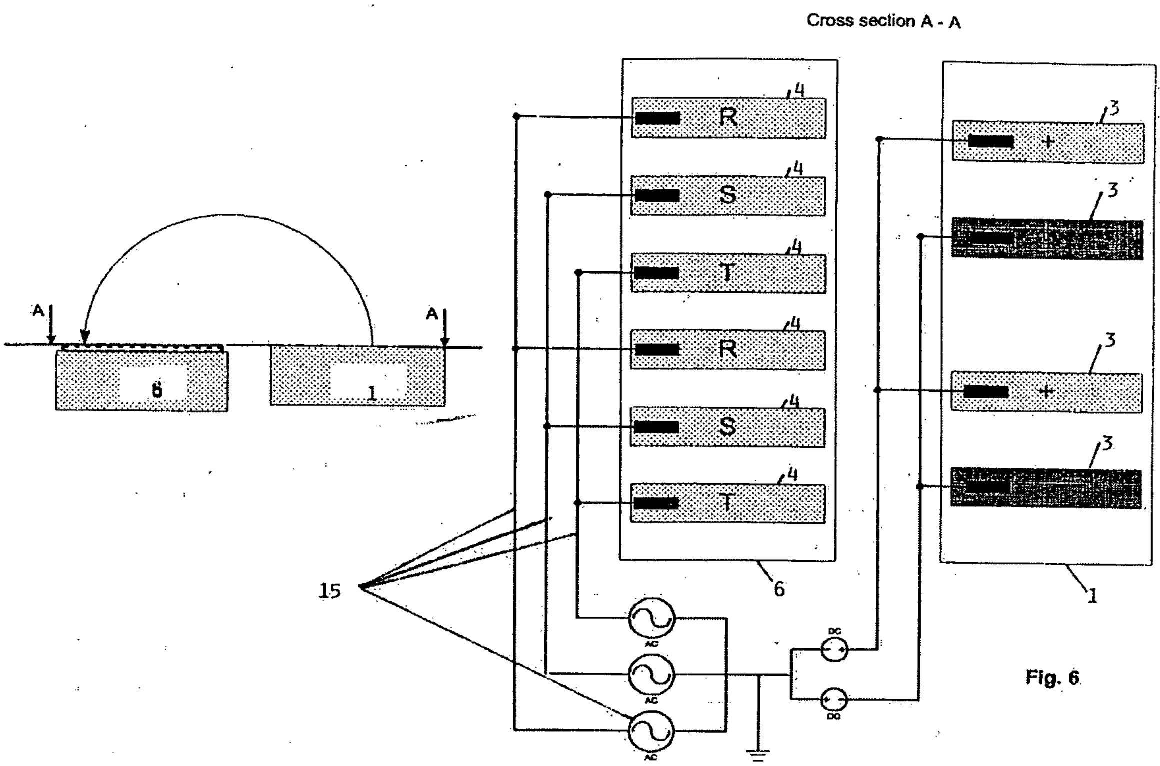

Fig. 6

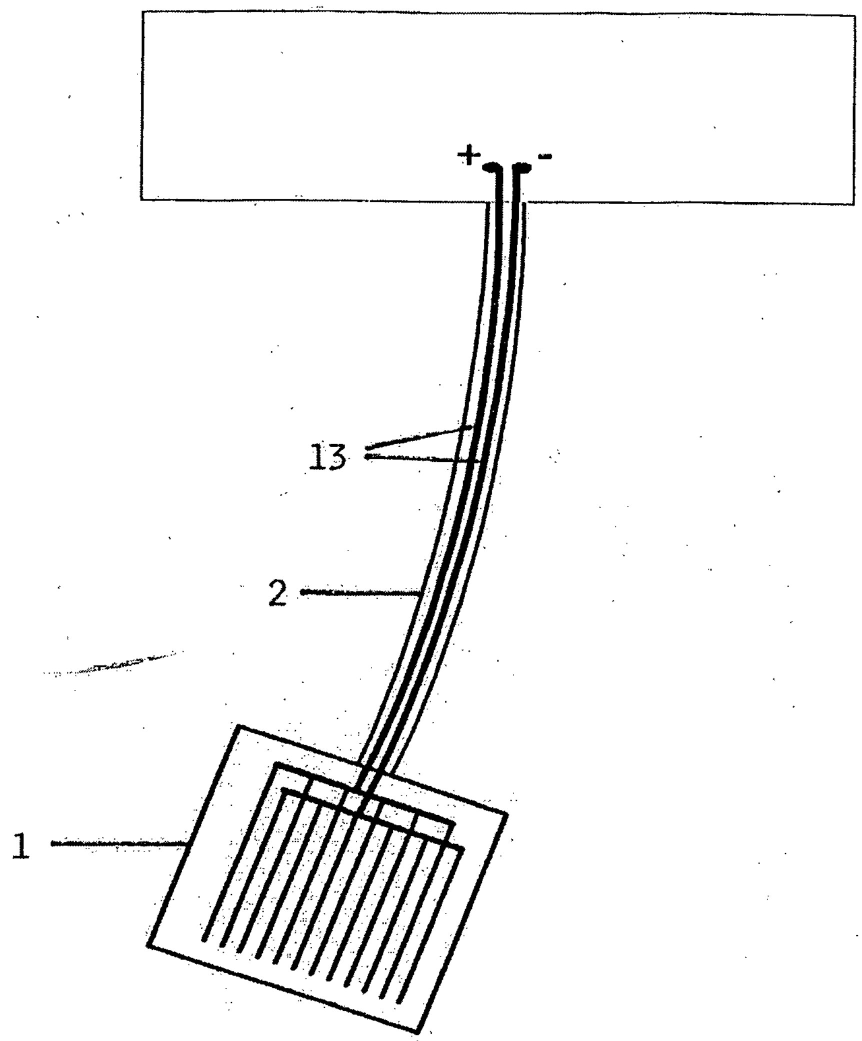

Fig. 7

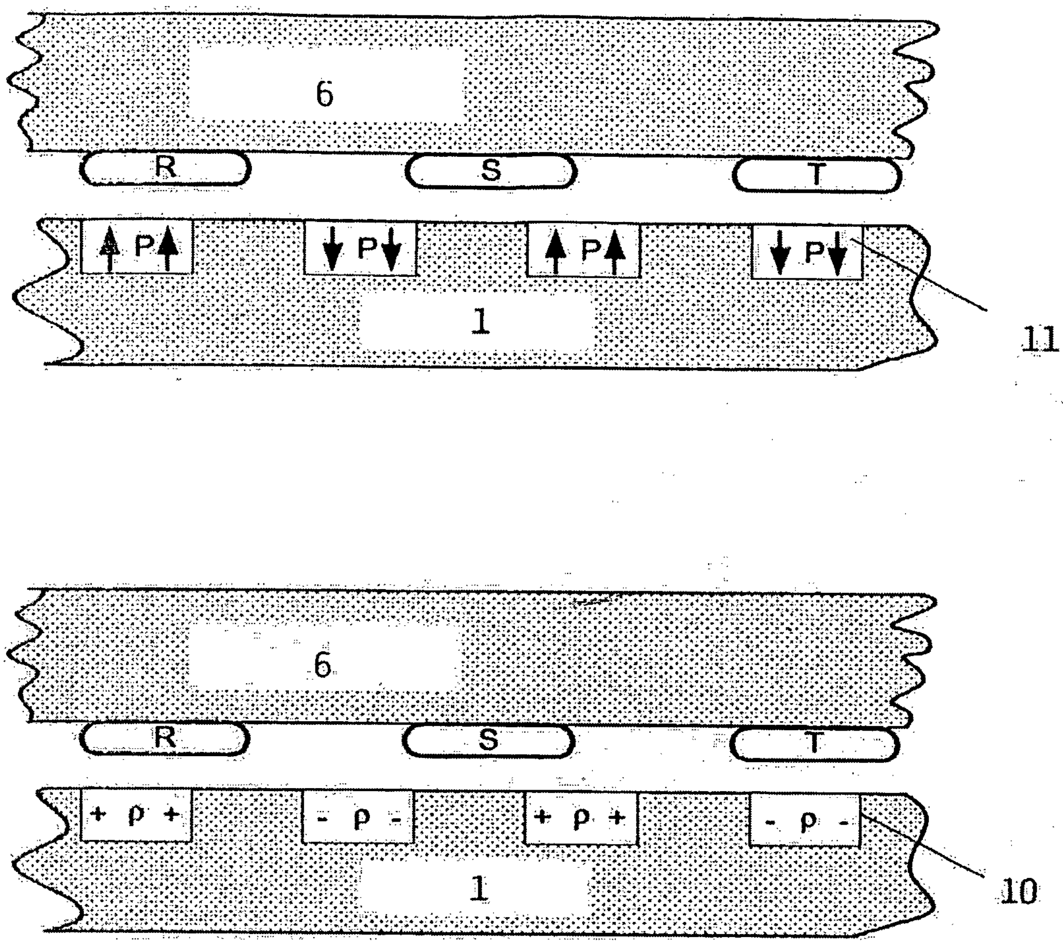

Fig. 8

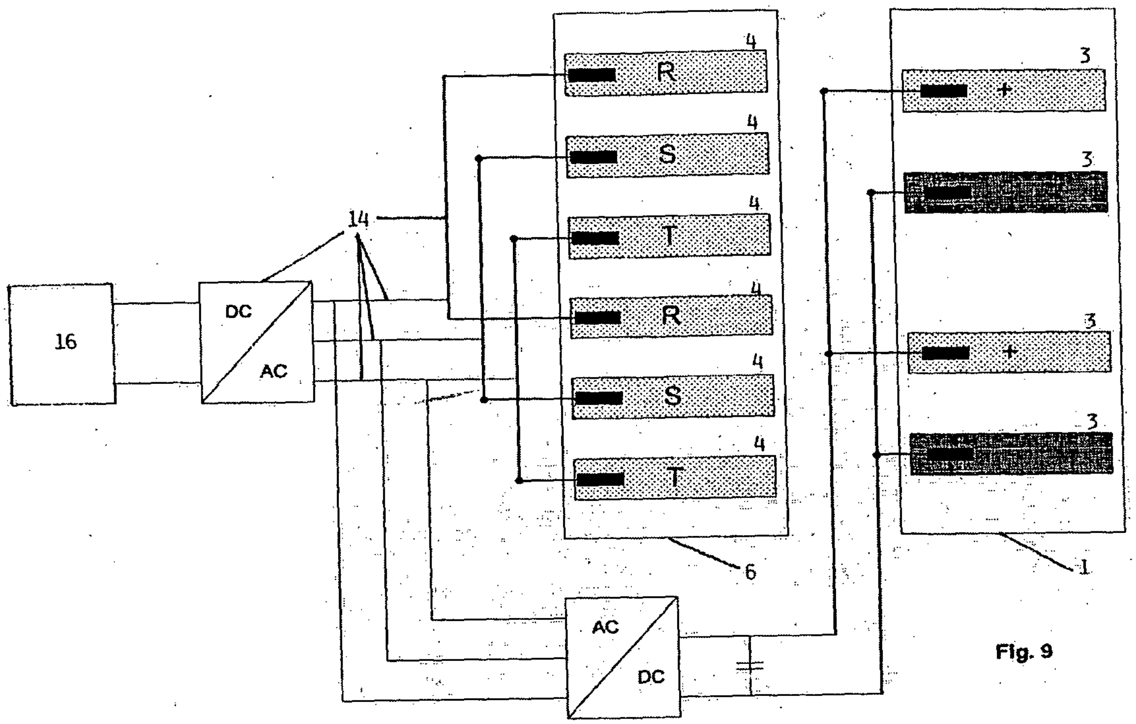

Fig. 9

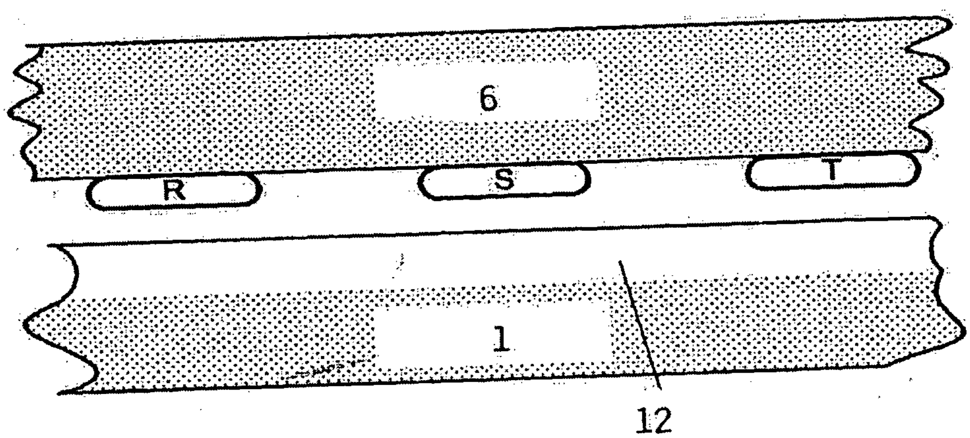

Fig. 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IB 02/05575

A. CLASSIFICATION OF SUBJECT MATTER

IPC7: H02N 3/00, B81B 7/02, F03B 17/06
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC7: H02N, B81B, F03B, H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-INTERNAL, WPI DATA, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	C.B. Williams and R.B. Yates; "Analysis of a micro-electric generator for microsystems", Sensors and Actuators A: Physical, Volume 52, Issues 1-3,4 March 1996, Pages 8-11 see whole document	1
Y		2-14
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[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
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"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance: the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
25 March 2003	26 -03- 2003
Name and mailing address of the ISA/ Swedish Patent Office Box 5055, S-102 42 STOCKHOLM Facsimile No. +46 8 666 02 86	Authorized officer Antonio Farieta/MN Telephone No. +46 8 782 25 00

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	Niino, T. Egawa, S. Higuchi, T.: Dept. of Precision Mach. Eng., Tokyo Univ.; "High-power and high-efficiency electrostatic actuator"; Micro Electro Mecannical Systems, 1993, MEMS'93, Proceedings' An Investigation of Micro Structures, Sensors, Actuators, Machines and Systems'. IEEE. 7-10 Feb 1993, Fort Lauderdale, FL, USA: On page(s): 236-241 see whole document --	2-14
A	US 2001/029911 A1 (WEI YANG ET AL) 18 October 2001 (2001-10-18) page 1 paragraph [0004] page 2 paragraph [0012] -- --------	1-14

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ABSTRACT:

CHG DATE=20051223 STATUS=O>A micro-electromechanical energy transformer comprising a stationary element (6) with a planar surface and a movable element (1) with a planar surface (1) arranged in such a manner that an air gap arises between the two plane surfaces (1). A first electrode system (4) belonging to the stationary element (1) and co-operating means (3) belonging to the movable element (1) create an electrical field in the air gap. The movable element (1) is integrated in an elastic mechanical element (1,2) such that the movement takes place through bending, for instance oscillation, of the elastic mechanical element (1,2).